Indian J Phys. 82 (11), 1429-1440 (2008)

Class transitions of compact objects Cygnus X-1 and Cygnus X-3

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Received 5 May 2008, accepted 29 May 2008

Abstract : We present the evidences of class transitions (transitions from one type of light curve to the other) of light curves by analyzing the X-ray data obtained from IXAE and RXTE of the two compact objects Cygnus X-1 and Cygnus X-3 It is also observed from the Power Density Spectrum (PDS) that during class transitions the slope of the PDS changes but the slope remains same when there is no transition We observe that the class transitions take place in a matter of minutes Thus the variation in the accretion rates, which is thought to be the sole cause of the class-to-class variation, must be nearly freely falling like other black hole candidates such as GRS 1915+105

Keywords : Compact objects, Cygnus X-1, Cygnus X-3, X-rays

PACS Nos. : 97 60Lf, 97 30 Qt

1. Introduction

Cygnus X-1, the brightest hard X-ray binary source, is considered to be one of the most firmly established persistent Galactic Black Hole Candidate (GBHC) Since its discovery in a rocket flight in 1964 [1], it has been intensively observed in almost all X-ray astronomy missions. Its optical companion star, HDE 226868, is an O9-B0 supergiant of magnitude 8.84 [2] with an effective surface temperature of 32000 K [3] and observed radial velocity of 76 km/s [4]. HDE 226868 is an O9.7Iab spectral type [5] star almost filling the Roche lobe [6, 7]. It is positioned at right ascension of $19^h58^m21^s.70$ and declination of $+35^o12'5''.82$ [8]. The mass of the compact object, as obtained from photometric modulations, is estimated to be 8 ± 3 $M_\odot$ and that of the companion star to be 16 ± 2

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$M_\odot$ [9, 10]. Spectroscopic observations show that the spectral lines of HDE 226868 shift back and forth with a period of 5.59974(8) days, where the value in parentheses is uncertainty in units of the last digit [4]. Cygnus X-1 and its optical companion emit luminosities of 4×10^{37} erg/s and 10^{39} erg/s respectively [3, 11] and the system is at a distance of 2.5 kpc [7]. Herrero *et al* [3] estimated the radius of Cygnus X-1 to be equal to 30 km and that of HDE 226868 to be $17R_\odot$. The mass loss rate of the system is found to be 3×10^{-6} $M_\odot$ per annum [3].

Cygnus X-1 exhibits a bimodal behaviour with two distinct spectral states "hard" and "soft" and it is known to make transition from one state to the other irregularly [12] Though most of the time it is observed in the hard state. It is characterized by rapid and chaotic intensity variations over time scales of milliseconds to several seconds and days On several occasions quasi-periodic oscillations have also been detected from it. It is observed that spectral transition of Cygnus X-1 from one state to the other is associated with a change in power density spectrum (PDS). In the soft state of Cygnus X-1 the intensity variations are less pronounced compared to that in the hard state. The hard state power density spectrum is found to be flat below a frequency of about 0.1 HZ and it decreases above that value [13, 14]. Weisskopf *et al* [15] explained the X-ray variabilities as the sum of randomly occurring X-ray shots and a steady emission. The shots are most likely to be due to local "hot spots" formed in the accretion disk. They may be either symmetric in shape with exponential rise and decay or asymmetric with sharp rise and exponential decay. Negoro *et al* [16] studied the properties of X-ray shots of Cygnus X-1 in the low state with the large area proportional counters on-board the Ginga satellite Rao *et al.* [17] also investigated the X-ray shots from Cygnus X-1 extensively using data obtained from IXAE.

According to the Two component Advective Flow (TCAF) model of Chakrabarti and Titarchuk [18] the inner boundary condition of the black hole forces the matter to deviate from Keplerian distribution. Therefore the accretion disk consists of two parts, a Keplerian component of high viscosity and high angular momentum at the equatorial plane and a sub Keplerian component of low viscosity and low angular momentum that resides above and below the Keplerian component. The sub Keplerian component can form a standing shock wave or, CENtrifugal pressure supported BOundary Layer (CENBOL). The wide band X-ray spectrum of Cygnus X-1 qualitatively agrees with this model [19]. To explain qualitatively the spectral behaviour and spectral states of Cygnus X-1 Narayan and Yi [20] have used their model based on advection dominated accretion flows in black holes.

Cygnus X-3 is an X-ray binary source, which was discovered by R Giaconni [21] in 1966 during an X-ray survey sensitive in the energy range 2–5 keV. Located in the galactic plane at a distance of ~ 10 kpc, having right ascension of $20^h30^m52^s$ and declination of 40°56' [21], it has an orbital period of 4.8 hour [22–24]. The companion star of the compact object is a WR star [25], which is invisible in the optical band but can be clearly seen above 8000 Å. Much debate has been left regarding the nature of Cygnus X-3 though it is not yet established whether it is an X-ray pulsar, a black hole or low magnetic neutron star [26, 27].

Like Cygnus X-1, Cygnus X-3 is characterized also by two spectral states low – hard and high – soft and has been observed up to 500 keV during flare mode Cygnus X-3 exhibits quasi-periodic oscillations with periods in the range 50 – 1500 s [28] At radio frequencies Cygnus X-3 is one of the most luminous and persistent source among the X-ray binaries It frequently exhibits huge radio flares, which occur during the high-soft X-ray state Manchanda [29] showed by a detailed analysis of X-ray spectrum that the total number of X-ray photons remains conserved at all times and in all states Choudhury *et al* [30] studied the correlation between soft and hard X-ray and radio emissions of Cygnus X-3 They showed a positive correlation between soft X-ray and radio emission in the hard state of the source and an anti-correlation between soft and hard X-ray emissions

The class transition is not a new phenomenon Different types of class transitions have already been observed in GRS 1915 + 105 by analyzing the X-ray data of IXAE [31–33] Now, in this paper we are going to show direct evidence of spectral class transitions (both from hard to soft and soft to hard) of Cygnus X-1 and Cygnus X-3 using data obtained from the Indian X-ray Astronomy Experiment (IXAE) which was launched on March 21, 1996 from Sriharikota range in India on-board the Indian Remote Sensing Satellite IRS-P3 using the Polar Satellite Launch Vehicle (PSLV) [34] At an altitude of 830 km and inclination of 98^o the satellite is in a circular orbit including collimated Pointed Proportional Counters (PPCs) with an effective area of about 1200 cm^2 The PPCs are filled with a mixture of gases containing 90% argon and 10% methane at a pressure of 800 mmHg Each PPC is a multi-anode, multi-layered detector and contains 54 anode cells of size 11 cm × 11 cm arranged in three layers with a well-less geometry [35] The operating energy range is 2–18 keV with an overall energy resolution of 22% at 6 keV The photon counts are saved in the archive in two channels , 2–6 keV and 6 – 18 keV The time resolution in the normal mode is set at 1s but in the medium mode it could be 0 1s We have analyzed those data that are free from South Atlantic anomaly (SAA) and occultation due to earth

2. Observation and data analysis

2 1 Light curve and mean photon index

We have analyzed the X-ray photon counts of two compact objects Cygnus X-1 and Cygnus X-3 obtained from the IXAE of all channels 2–6, 6–18 and 2–18 keV In the upper and lower panels of Figures 1–7 we have shown respectively the light curves in which photon count rate is plotted against time and the variation of mean photon index S_Φ with time The mean photon index S_Φ is defined as [32]

$$S_\Phi = \frac{\log(N_{6-8}/E_2) - \log(N_{2-6}/E_1)}{\log(E_1) - \log(E_2)} \tag{1}$$

where N_{2-6} and N_{6-18} are the photon count rates from the top layer of the PPC corresponding to the energy range 2–6 keV and 6–18 keV respectively E_1 and E_2 are the mean energies of the channels, *i e* E_1 = 4 keV and E_2 = 12 keV We have used the FTOOLS package of NASA for the purpose of data analysis

We have presented the log of observations of spectral class transitions reported in this paper in Table 1 The first and the second columns represent the figure numbers of light curves and power density spectra The third column refers to the compact object concerned The fourth column shows the data of observation The fifth column gives the name of the satellite from which data is obtained The orbit numbers or channels, depending upon the satellite, plotted in different figures is given in the sixth column The time interval between successive orbits of IXAE is approximately 80 minutes The last column represents the nature of class transition, *i e* hard class to soft class, soft class to hard class or no transition

Table 1 Spectral class transition of Cygnus X-1 and Cygnus X-3

Figure No		Name of the object	Date of Observation	Name of the Satellite	Orbit No / Channels	Class Transition
Light curve	PDS					
1	8	Cygnus X-1	May 7 1996	IXAE	2	Hard to soft
2	9	Cygnus X-1	July 6 1996	IXAE	3	Soft to hard
3	10	Cygnus X-1	July 7 1996	IXAE	2	Soft to hard
4	11	Cygnus X-1	July 8 1996	IXAE	2	Soft to hard
5	12	Cygnus X-3	July 8 1999	IXAE	4	Hard to soft
6	13	Cygnus X-3	October 15 1999	IXAE	3	Hard to soft
7	14	Cygnus X-3	October 26 1999	IXAE	4	Hard to soft
15	16	Cygnus X-1	May 1 1996	IXAE	2	No transition
17	18	Cygnus X-3	July 4 1999	IXAE	3	No transition
19	20	Cygnus X-1	May 22 1996	RXTE	0-35	No transition

2 1 1 Object Cygnus X-1

The upper panel of Figure 1 shows the light curve (2–18 keV) of Cygnus X-1 in the 2nd orbit of May 7, 1996 For the first 550 s the object is seen to be in the hard class with an average photon count rate of 50 per second After that it has suffered a rarely observed class transition from hard class to soft class corresponding to a mean photon count per second of more than 200 At the end (960 s) the light curve shows a tendency of attaining higher value (800 counts per second) It is seen from the lower panel of the figure that the value of the mean photon index (S_Φ) changes from –3 7 to 0 2 before transition But after the transition it varies between –1 8 and –0 8 Therefore the hard to soft class transition is accompanied by a reduction in noise of S_Φ

The light curve of Cygnus X-1 as observed by the IXAE on July 6, 1996 in the 3rd orbit is shown in the upper panel of Figure 2 The compact object is seen to undergo a transition from soft class (first 180 s) corresponding to mean photon count per second of about 600 to hard class characterized by mean photon count rate of 30 per second The lower panel of the figure depicts that prior to transition the mean photon index (S_ϕ) shows a steady nature by confining itself close to – 1 0, but after transition it becomes turbulently varying In the hard class S_ϕ is found to fluctuate between – 3 8 and 1 0 Thus the soft to hard class transition is associated with an increase in the noise level of S_ϕ

The light curve for the observation of Cygnus X-1 by the IXAE for the 2nd orbit of July 7, 1996 is shown in the upper panel of Figure 3 In the soft class (up to about 200 s) the average photon count per second is about 350 In the hard class its mean value is about 25 As can be seen from the lower panel of the figure, the noise level of S_ϕ is increased dramatically after the transition Fluctuations of S_ϕ changes from the range of – 2 0 to –1 0 to the range of –3 8 to 1 0

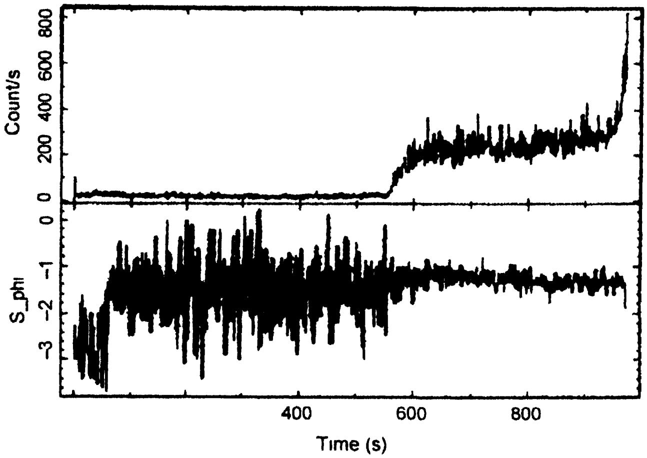

Figure 1. 2–18 keV light curve of Cygnus X-1 as observed by IXAE (upper panel) and mean photon index (S_ϕ) (lower panel) in the 2nd orbit of May 7 1996 The compact object makes transition from hard class to soft class S_ϕ becomes less noisy after the transition

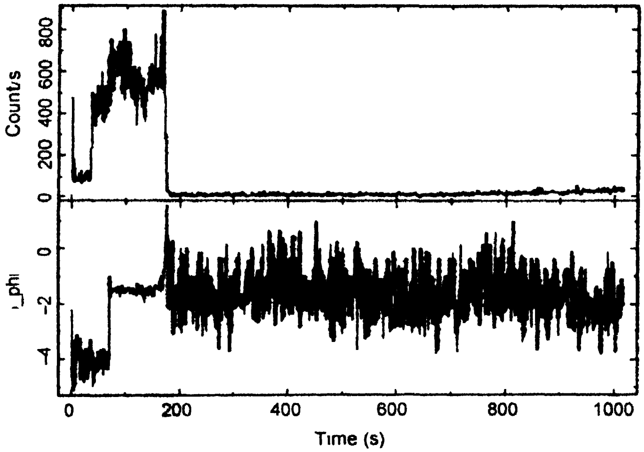

Figure 2. 2–18 keV light curve (upper panel) and S_ϕ (lower panel) for the 3rd orbit of July 6 1996 in which Cygnus X-1 changes from soft class to hard class Noisy character of S_ϕ can be seen after transition into hard class

Again in the upper panel of Figure 4 we have shown the light curve of Cygnus X-1 using data of IXAE obtained in the 2nd orbit on July 8, 1996 The average photon count rate in the soft class (up to about 185 s) is 400 per second, whereas its value in the hard class is 20–25 per second Similar to previous cases the noisy character of mean photon index is found to become very pronounced in the hard class as it is revealed from the

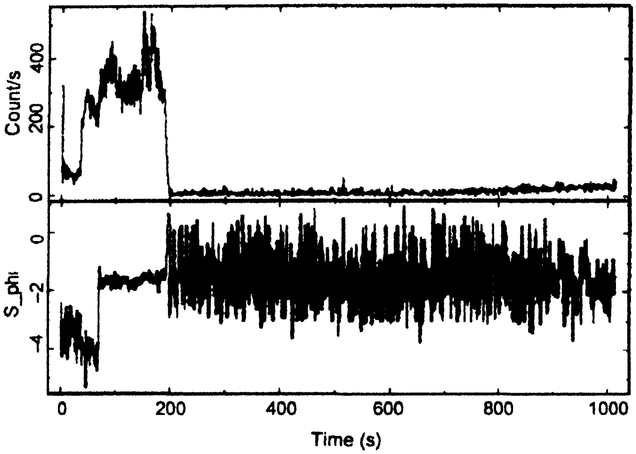

Figure 3. Soft to hard class transition of Cygnus X-1 The upper panel shows the light curve in the 2–18 keV range of IXAE data for July 7, 1996 in the 2nd orbit. The lower panel shows the variation of S_Φ which is very noisy in the hard class

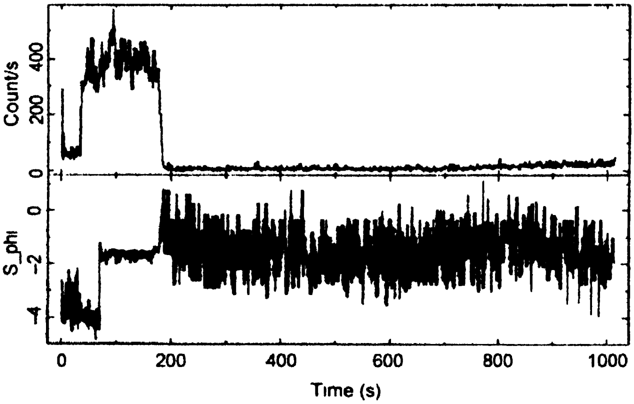

Figure 4. Light curve (upper panel) and S_Φ (lower panel) for the IXAE observation of Cygnus X-1 in the 2–18 keV range on July 8, 1996 in the 2nd orbit. it undergoes a transition into hard class after 180 s in the soft class. Hard class fluctuation of S_Φ is very pronounced.

lower panel of the figure. Whereas S_Φ restricts itself between –2.0 and –1.5 in the soft class, it varies from –4.0 to 1.0 in the hard class.

2.1.2 Object Cygnus X-3 :

The light curve of Cygnus X-3 for the 4th orbit of July 8, 1999 is shown in the upper panel of Figure 5. It can be seen that the object is in hard class during the first 400 s with an average photon count rate of about 25 per second. Then there is a transition from hard class to soft class and the average photon count per second becomes nearly 100 which is about four times of that in the hard class. The lower panel of the figure shows the variation of mean photon index (S_Φ) with time It is seen that S_Φ changes from –3.35 to 0.5 in the hard class but in the soft class it fluctuates between –1.4 and 0 1

The upper panel of Figure 6 shows the light curve of Cygnus X-3 for the 3rd orbit of October 15, 1999. During the first 500 s the average photon count per second is about 20 and the object is in the hard class. After that it makes transition to soft class with a mean photon count rate of above 85 per second over a period of 575 s. S_Φ is seen to fluctuate between – 3.5 and 1.0 before transition and between –0.8 and 2.3 after transition. So S_Φ becomes less noisy after the transition.

We have shown the light curve of Cygnus X-3 for the 4th orbit of October 26, 1999 in the upper panel of Figure 7. It can be seen very clearly that Cygnus X-3 suffers a transition from hard class to soft class after 600 s. In the hard class the average photon count per second is 20 but in the soft class it becomes about 350. So there is a large difference of photon count rate in the two classes. Again the mean photon index (S_Φ) is found to become less noisy after the transition The fluctuation of S_Φ lies between −2 9 and 1 3 in the hard class But in the soft class the value of S_Φ varies within the range from 0 2 to 0 5

2 2 *Power Density Spectrum*

We have obtained power density spectrum (PDS) for all of the observations mentioned earlier, both of Cygnus X-1 and Cygnus X-3, and they are shown in Figure 8–14 respectively We have found no QPO in any of the cases In the very transiton dates we have detected an important feature in the power density spectra Each of the observed power density spectra is characterized by a break in slope at a particular frequency Above and below that particular frequency the PDS can be fitted by power-law of two different slopes

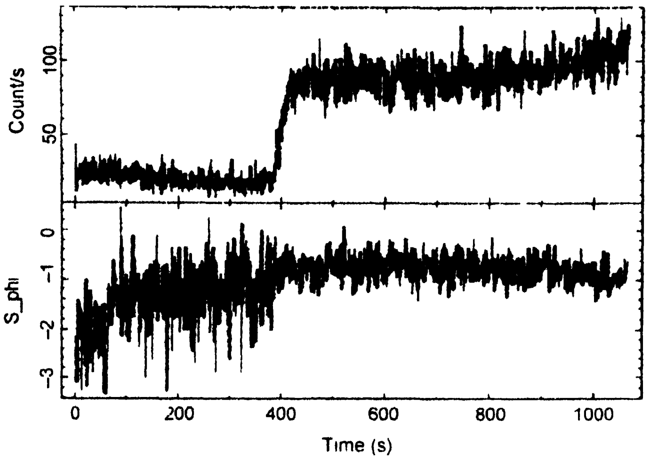

Figure 5. Transition of Cygnus X-3 from hard class to soft class The upper panel shows the 2–18 keV light curve of July 8 1999 in the 4th orbit of IXAE The lower panel shows the nature of S_Φ In the hard class (first 400 s) the photon count rate is low but the fluctuation of S_Φ is high compared to the soft class

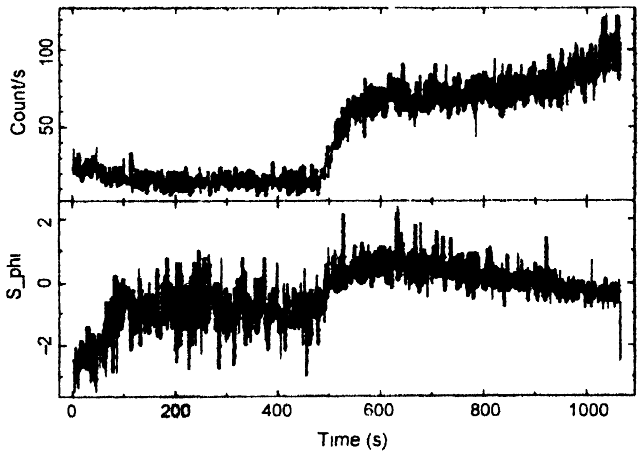

Figure 6 Hard to soft class transition of the compact object Cygnus X-3 as observed the IXAE in the 3rd orbit of October 15 1999 The upper panel shows the light curve (2–18 keV) and the lower panel shows the variation of S_Φ

2 2 1 *Object Cygnus X-1*

Figure 8 shows the PDS of Cygnus X-1 for the 2nd orbit of May 7, 1996 The power-law index for frequency below 0 1 HZ is − 1 45 and above 0 1 Hz it is − 1 19

The PDS of Cygnus X-1 for 3rd orbit of July 6, 1996 is plotted in Figure 9 It can be fitted by a power-law of index − 1 6 below a frequency of 0 1 Hz Above this frequency the PDS becomes flat with a power-law index − 0 7

In Figure 10 we have shown the PDS of Cygnus X-1 for the 2nd orbit of July 7, 1996 It is very clear that there is a break in slope at 0 1 Hz Below this frequency the power-law index is − 1.9 and above this frequency the value is −0 07 which indicates that the PDS becomes very much flat

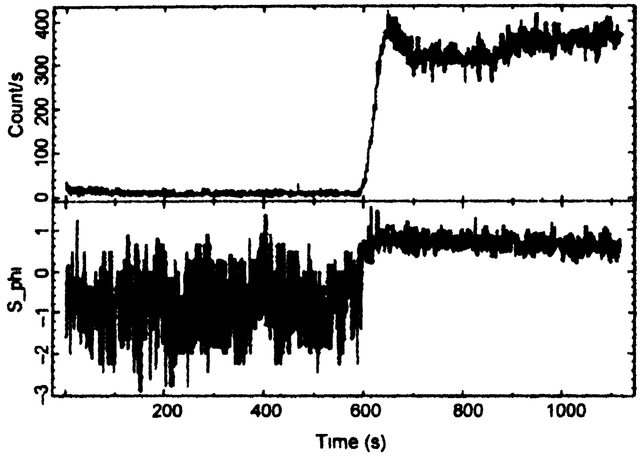

Figure 7. 2–18 keV light curve (upper panel) and the corresponding variation of S_Φ (lower panel) indicating a hard to soft class transition of Cygnus X-3 as observed by the IXAE on October 26, 1999 in the 4th orbit

For the 2nd orbit of July 8, 1996 the PDS of Cygnus X-1 is shown in Figure 11 The PDS is steep below a frequency of 0 1 Hz with a power-law index of –1 8 Above this frequency the PDS becomes flat with a power-law index of –0 5

2 2 2 Object Cygnus X-3

It is observed that the break is slope of PDS is at 0 1 Hz in all the cases of Cygnus X-1 But the break is seen to occur at different frequencies for Cygnus X-3 The PDS for the IXAE observation of Cygnus X-3 in the 4th orbit of July

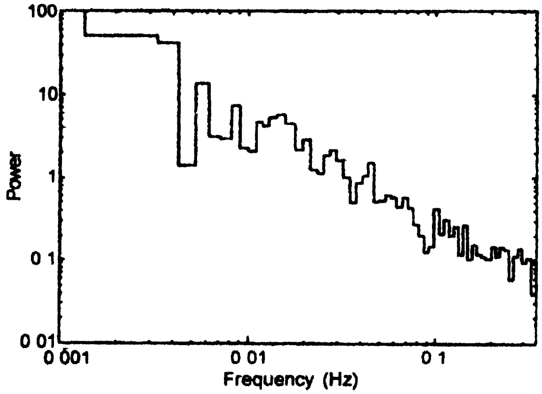

Figure 8. PDS of Cygnus X-1 for the 2nd orbit of May 7, 1996

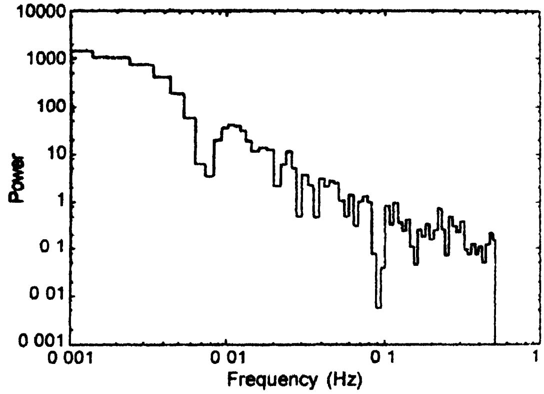

Figure 9. PDS of Cygnus X-1 for the 3rd orbit of July 6, 1996

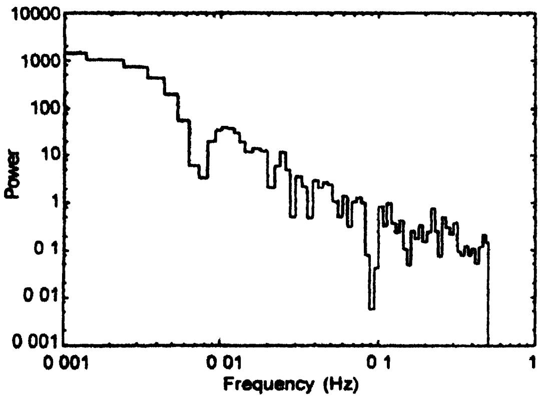

Figure 10. PDS of Cygnus X-1 for the 2nd orbit of July 7, 1996

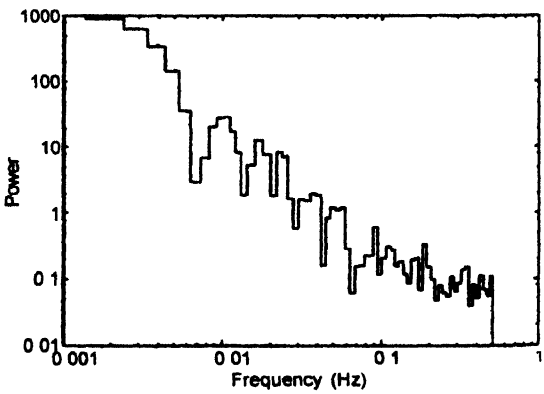

Figure 11. PDS of Cygnus X-1 for the 2nd orbit of July 8, 1996

8, 1999 is depicted in Figure 12 Here the break up frequency is 0.03 Hz and the power-law indices below and above this frequency are respectively – 2 15 and –0.6.

Again the PDS of Cygnus X-3 observed in the 3rd orbit on October 15, 1999 is plotted in Figure 13 The PDS has a break at 0.04 Hz. The index of power-law before the break is –2 2 and after the break it has a value of –0 6

The power density spectrum of Cygnus X-3 for the IXAE observation in the 4th orbit of October 26, 1999 indicates a very prominent flattening after the break-up at 0 07 Hz as shown in Figure 14 For frequencies below 0.07 Hz the PDS has a power-law of index –2 3 But in index becomes – 0 65 for frequencies above 0 07 Hz

In Figure 15 a typical soft class light curve and the corresponding mean photon index (S_{Φ}) *vs* time variations are plotted in two panels for the IXAE observation of Cygnus X-1 in the 2nd orbit of May 1, 1996 The PDS of that date is shown in Figure 16 The power-law index is –0.15 and there is no indication of break in slope of the PDS. We obtain similar results for an IXAE observation of Cygnus X-3 in its soft class in the 3rd orbit of July 4, 1999. The light curve along with the mean photon index *vs.* time plot are shown in two different panels of Figure 17 and the corresponding PDS is shown in Figure 18. In this case the power-law index is –0.5 and there in no break in the slope of the PDS.

We have also analyzed the data obtained by RXTE for several dates so

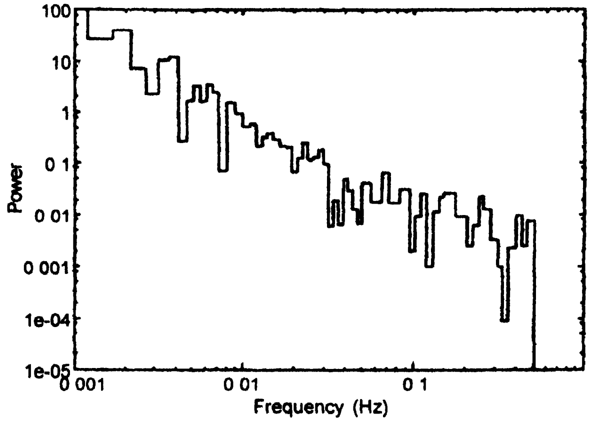

Figure 12. PDS of Cygnus X-3 for the 4th orbit of July 8, 1999

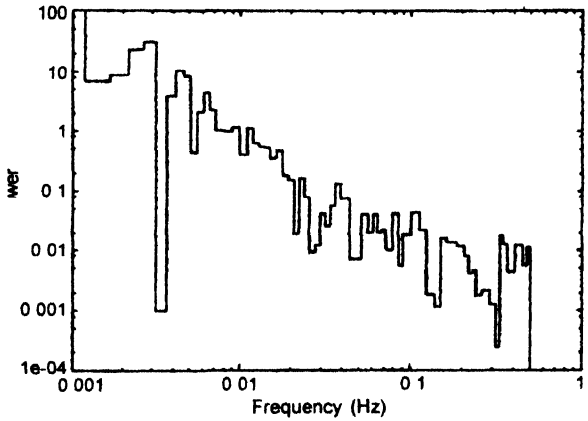

Figure 13. PDS of Cygnus X-3 for the 3rd orbit of October 15, 1999

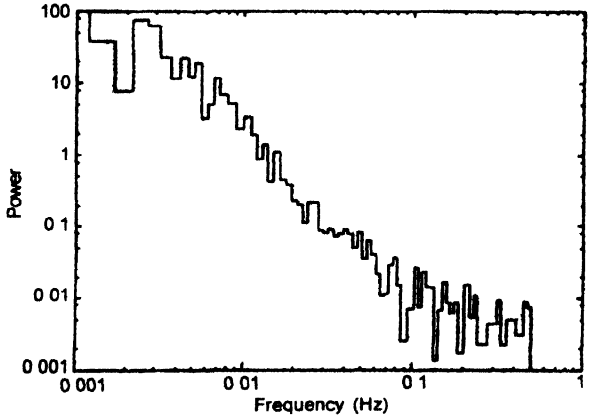

Figure 14. PDS of Cygnus X-3 for the 4th orbit of October 26, 1999

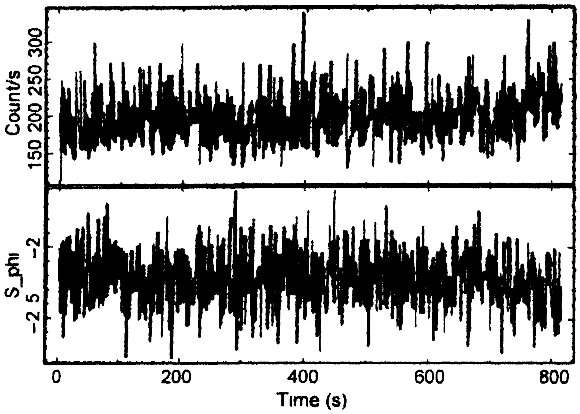

Figure 15 Light curve (upper panel) in the 2–18 keV range and mean photon index (S_Φ) (lower panel) for the IXAE observation of Cygnus X-1 (in its soft class) in the 2nd orbit of May 1, 1996

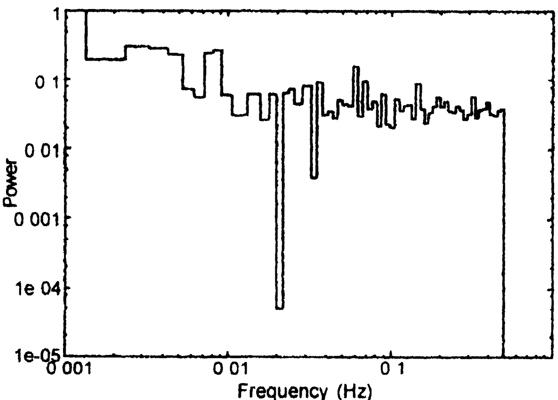

Figure 16. PDS of the observation corresponding to light curve of Figure 15 There is no break in the slope of the PDS

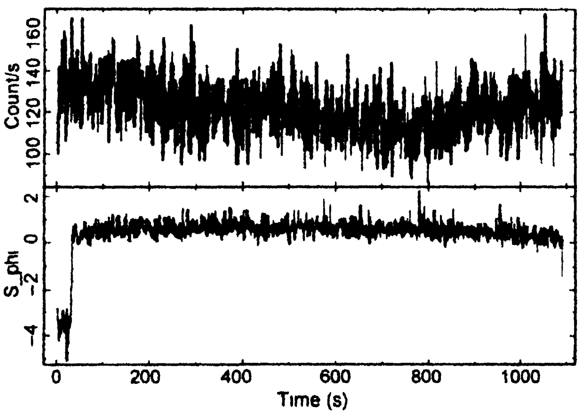

Figure 17. Upper panel 2–18 keV light curve of Cygnus X-3 for the IXAE observation on July 4, 1999 in the 3rd orbit .Lower panel The variation of S_Φ

far available in NASA archive but have not found any spectral class transition of Cygnus X-1 and Cygnus X-3 Nevertheless, we have verified the nature of PDS of RXTE observation of Cygnus X-1 in its soft class on May 22, 1996 The light curves along with the variation of S_Φ and PDS for this date are shown respectively in Figure 19 and Figure 20 In this case S_Φ is calculated by taking photon count rates in the energy ranges 1 94–5 82 keV and 6 18 – 12 99 keV corresponding to channels 0 – 15 and 16 – 35 respectively It is seen that the PDS can be fitted by a simple power-law of index –0 7 without any break in slope

3. Conclusions

In this paper, we have presented the direct evidence of class transitions of light curve from one class (soft) to another class (hard) and *vice versa* for two sources Cygnus X-1 and Cygnus X-3 by using the X-ray photon counts obtained from the Indian X-ray Astronomy Experiment satellite We found the hard class to soft class of light curve transitions for the source Cygnus X-1 and May 7 and soft class to hard class on July 6, July 7 and July 8, 1996 The hard class to soft class of light curve transitions for the source Cygnus X-3 were observed on July 8, October 15 and October 26, 1999 We have also presented two light curves, one with IXAE data on May 1, 1996 and the other with RXTE data on May 22, 1996 where there are no transitions It is observed that the mean photon index (S_Φ) becomes noisy during transition and no noises when there is no

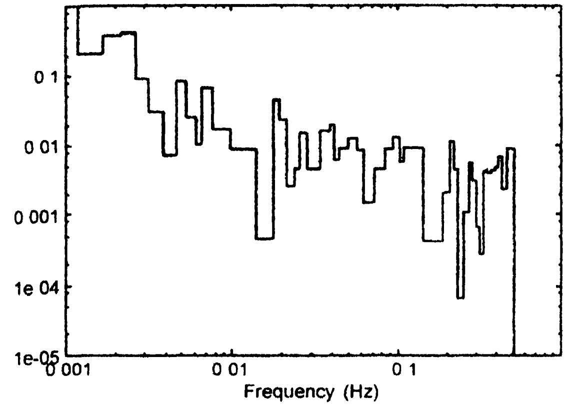

Figure 18. PDS of the observation corresponding to light curve of Figure 17 The slope of the PDS is constant

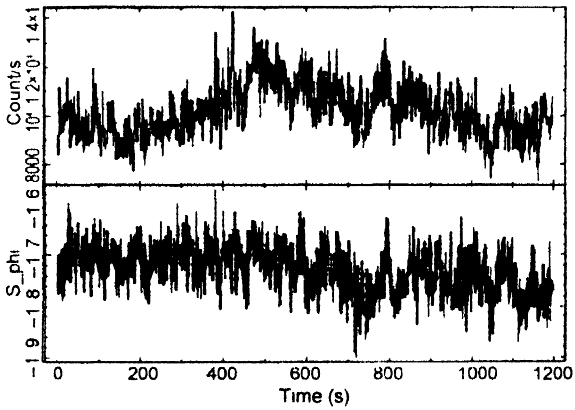

Figure 19. Upper panel Light curve of Cygnus X-1 for the RXTE observation on May 22 1996 using 0–35 channels Lower panel Mean photon index *vs* time plot

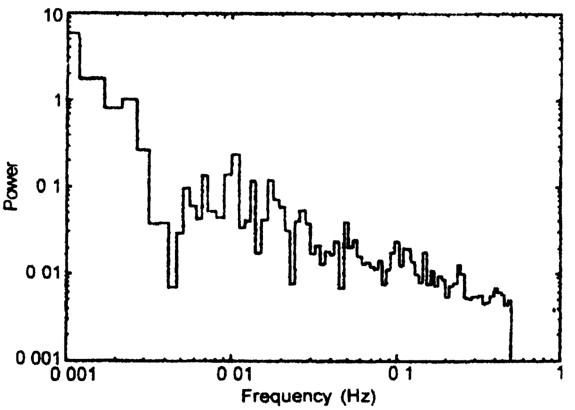

Figure 20. PDS of the observation corresponding to light curve of Figure 19 The slope of the PDS remains unchanged

transition We showed that during transition photon count rates were rapidly changing, which indicates the change in accretion rates This indicates the free falling sub-Keplerian flow may be present in the accretion flow of the compact objects (Cygnus X-1 and Cygnus X-3), which supports the conclusion of Smith *et al* [36, 37] Our observations also confirm that as a compact object (Cygnus X-1 or Cygnus X-3) makes transition from one spectral class to another, the slope or index of power-law of the power density spectra changes at some break-up frequency supporting the earlier conclusion of Cui [38], Paul [39] and Rao *et al* [17]

Acknowlegments

We acknowledge the contribution of scientific and technical staff of IXAE team The authors thank Prof P C Agarwal for allowing the IXAE data analysed in this paper to be placed in the ISRO sponsored databank at Indian Centre for Space Physics We also thank Prof S K Chakrabarti for discussions

References

[1] S Bowyer, E T Byram T A Chubb and M Friedman *Science* **147** 394 (1965)

[2] ESA (eds) *The Hipparcos and Tycho Catalogues ESA* SP 1200 (Noordwijka ESA Publications Division) (1997)

[3] A Herrero, R P Kudritzki R Gabler, J M Vilchez and A Gabler *Astron Astrophys* **297** 556 (1995)

[4] D R Gies and C T Bolton *Astrophys* **260** 240 (1982)

[5] N R Walborn *Astrophys* **179** L123 (1973)

[6] C T Bolton *Nature* **235** 271 (1972)

[7] Z Ninkov, G A H Walker and S Yang *Astrophys* **321** 425 (1987)

[8] C Turon, M Crézé, D Egret, A Gömez *et al, The Hipparcos Input Catalogue* ESA-SP **1136** (Noordwijk ESA Publications Divisions), (1992)

[9] N I Balog, A V Goncharskiî and A M Cherepashchuk *Sov Astron Lett* **7** 336 (1981) [(orig *Pis'ma Astron Zh* **7** 605 (1981)]

[10] J B Hutchings *Astrophys* **226** 264 (1978)

[11] E P Liang and P L Nolan *Space Sci Rev* **38** 353 (1984)

[12] S N Zhang, W Cui, B A Harmon *et al, Astrophys J* **477** L95 (1997)

[13] P L Nolan, D E Gruber, F R Knight, J L Matteson, R E Rothschild, F E Marshall, A M Levine and F A Primini *Nature* **293** 275 (1981)

[14] T Belloni and G Hasinger *Astron Astrophys* **227** L33 (1990)

[15] M C Weisskopf, S M Khan and P G Sutherland *Astrophys J* **199** L147 (1975)

[16] H Negoro, S Miyamoto and S Kitamoto *Astrophys J* **423** L127 (1994)

[17] A R Rao, P C Agarwal, B Paul, M N Vahia, J S Yadav, T M K Marar, S Seetha and K Kasturirangan *Astron Astrophys* **330** 181 (1998)

[18] S K Chakrabarti and L G Titarchuk *Astrophys* **455** 623 (1995)

[19] V R Chitnis, A R Rao and P C Agarwal *Astron Astrophys* **331** 251 (1998)

[20] R Narayan and I Yi *Astrophys* **428** L13 (1994)

[21] R Giaconni, P Gorenstein, H Gursky and J R Waters, *Astrophys* **148** L119 (1967)

[22] P Predehl, J Wilms, M A Nowak *et al, Proceedings of the 3rd Micro-quasar workshop* (ed) A J Castro-Tirado, J Greiner, J M Parades, (Dordrecht Kluwer), 41 (2002)

[23] J Dickey *Astrophys* **273L** 71 (1983)

[24] K O Mason and P W Sanford *MNRAS* **189P** 9 (1979)

[25] M H van Kerkwjick, T R Gebelle, D L King *et al, Astron Astrophys* **314** 521 (1996)

[26] W Schmutz, T R Gebelle and H Schild *Astron Astrophys* **311** L25 (1996)

[27] A Mitra *Astrophys* **499** 387 (1998)

[28] M van der Klis and F A Janson *Nature* **313** 768 (1985)

[29] R K Manchanda *J Astrophys Astr* **23** 197 (2002)

[30] M Choudhury, A R Rao, S V Vadawale, A K Jain and C H Ishwara-Chandra *Astron Astrophys* **383** L35 (2002)

[31] S K Chakrabarti, A Nandi, A K Choudhury and U Chatterjee *Astrophys* **607** 406 (2004)

[32] S K Chakrabarti, A Nandi, A K Chatterjee, A K Choudhury and U Chatterjee *Astron Astrophys* **431** 825 (2005)

[33] A K Choudhury, A K Chatterjee and A Nandi *Bull Astr Soc India* **35** 41 (2007)

[34] P C Agarwal in *Perspective in High Energy Astronomy and Astrophysics* (eds) P C Agarwal and P R Vishwanath (Hyderabad University Press) 408 (1998)

[35] B Paul, P C Agarwal, A R Rao, M N Vahia, J S Yadav, T M K Marar, S Seetha and K Kasturirangan *Astron Astrophys* **320** L37 (1997)

[36] D M Smith, W A Heindl, C B Markwardt and J H Swank *Astrophys* **554** 41 (2001)

[37] D M Smith, W A Heindl and J H Swank *Astrophys* **569** 362 (2002)

[38] W Cui IAUC 6404 (1996)

[39] B Paul *Bull Astr Soc India* **27** 103 (1999)